ELECTRICAL MEASUREMENTS ON SOIL WITH ALTERNATING CURRENTS.*

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SUMMARY.

The electrical properties of the earth play an important part in many modern applications of physics and electrical engineering. In the early portion of this paper a summary is given of the published information on the electrical properties of soil for alternating currents at frequencies from 50 to nearly 200 million cycles per sec. Particular interest is attached to the properties at radio frequencies, and it is shown that, while a certain amount of knowledge has been acquired by the use of field methods depending upon some characteristic of electric wave propagation, the results available apply to certain rather scattered ranges of frequencies and to some fairly localized portions of the earth's surface.

The later portions of the paper are concerned with the investigation of the conductivity and dielectric constant of samples of soil by a laboratory method of measuring resistance and reactance at radio frequencies. This method was used for the majority of the measurements which were carried out at frequencies between 100 and 10 000 kilocycles per sec., but, by the aid of a standard type of capacitance bridge, the work was extended through the audio-frequency range to a power frequency of 50 cycles per sec.

A series of preliminary measurements showed that reliable results could be obtained which were independent of the size and shape of the fixed condenser, in which the soil was packed as the dielectric. The conductivity and dielectric constant were both found to be very dependent upon the moisture content of the soil, except when this was within the normal range for the site under consideration. In a typical case the conductivity for dry soil, at a frequency of 1 200 kilocycles per sec., was of the order of 10^5 electrostatic units (corresponding to a resistivity of 9 megohms per cm cube), while at a moisture content of between 12 and 26 per cent a limiting value of between 10^8 and 2×10^8 electrostatic units (resistivity 9 000 to 4 500 ohms per cm cube) was obtained. The corresponding values of dielectric constant ranged from 3 or 4 for dry soil up to 30 or 40 for very moist soil. The effect of frequency on conductivity was more marked for dry than for moist soil, and in the latter case there was a small although definite rise in the conductivity at the highest frequencies. The dielectric constant decreased with increase of frequency towards a limiting value for moist soil, whereas for dry soil the variation of dielectric constant with frequency was very small. From measurements made on samples of different types of soil it was found that the temperature coefficient of the conductivity at 20° C. was about 2·3 per cent per deg. C., whereas the effect of temperature on the dielectric constant was negligible. In both cases, however, a sudden decrease in the value took place in passing through 0° C., which is attributable to the partial or total freezing of the water content.

When the validity of the laboratory method had been established, and it had been found that the results obtained thereby agreed with those previously available from field measurements, the investigation was extended to a study of the properties of soil from 12 different sites in England and Scotland. In the majority of these cases, samples of soil were obtained for measurement at various depths down to 10 ft., while in one case the depth was extended to 300 ft. The results are given in detail in tabular form in the paper. It is shown that, at a typical frequency of 1 200 kilocycles per sec., the conductivity of surface soil varies between $0{\cdot}16 \times 10^8$ and $4{\cdot}0 \times 10^8$ electrostatic units for different sites, while at various depths the values range from $1{\cdot}6 \times 10^5$ to about 10^{10} electrostatic units. In general it is shown that the clay soils have a high conductivity (i.e. above 10^8 electrostatic units) accompanied by high dielectric constant, and the loam and chalk soils an average value of about 10^8 electrostatic units for conductivity and 20 for dielectric constant, while soil of a sandy or gritty nature gives a much lower conductivity value. The lowest values (of the order of 10^5 electrostatic units) mentioned above were obtained on the solid granite or slate subsoils found at some of the sites.

The concluding section of the paper illustrates in graphical form the effect of the electrical properties of the soil on the penetration of alternating currents below the surface. Curves are plotted for certain of the sites from which samples of soil were obtained for measurement. These curves illustrate the fact that while at a frequency of 100 kilocycles per sec. a few per cent of the current at the surface may penetrate to a depth of 20 metres (over 60 ft.), at a frequency of 10 000 kilocycles per sec. the current is practically confined to the first 3 or 4 metres of depth. The effect of such current penetration on the field at the surface due to an electric wave being propagated along this surface is a subject that must remain for further investigation.

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(1) INTRODUCTION.

A knowledge of the electrical properties of the earth's surface is of considerable importance in physics and electrical engineering as well as in radio communication. Many investigators have employed electrical methods in exploring the ground for the presence of oil, minerals, etc., and some of these have become more or less standardized as useful tools in the general study of geophysics. In electrical engineering it is important to have efficient earth connections to the supply and distribution systems, and it is now well known that the resistance of such a connection is directly dependent upon the conductivity of the ground. In radio communication the electrical properties of the earth enter directly into the design of the transmitting installation, even in the case of a station employing an antenna array with no direct connection to earth. Further, the conductivity and dielectric constant of the ground are the dominating factors in determining the effective service area of broadcasting stations, in which the bulk of the communication is effected by the electric waves travelling along the surface of the earth. Finally, the efficiency of the receiving station is dependent upon the good conductivity of the ground upon which it is erected. The extending use of shorter wavelengths, with its consequent increase in the attenuation of the ground waves, has emphasized the importance of obtaining an accurate knowledge of the electrical properties of the ground. In addition to these applications it must be remembered that the soil physicist is interested in all the physical properties of various types of soil, and in particular in those which will provide him with any information as to the structural nature of the soil.

In order to form a clear idea as to the state of present knowledge on this subject, the first portion of the paper presents a summary of the literature indicating what information has already been obtained on the electrical properties of the earth. Various alternating-current methods have been used in this research, and, from the author's point of view, attention has been directed chiefly to the radio-frequency end of the spectrum, although the relevant material available at power frequencies has not been neglected.

The classical electromagnetic equations express the mode of propagation of electrical energy through a non-conducting medium having assigned values of dielectric constant and permeability, the velocity of propagation being calculable in terms of these quantities. If the medium has a finite conductivity, it is necessary to modify the equations by replacing the dielectric constant κ by the quantity

$$\kappa' = \kappa\left[1 - j \,.\, 2\sigma/(\kappa f)\right] \quad . \quad . \quad . \quad . \quad (1)$$

where σ is the conductivity, κ the dielectric constant, and f the frequency.

Defined in this way, the quantity κ' may be employed in all the equations required for the specification of the flow of alternating currents in conducting dielectrics. The factor j merely indicates the difference in phase of the conductance and displacement components of the current. It may be noted that in the extreme case in which $2\sigma/(\kappa f)$ is very small compared with unity, the conductivity has a negligible effect. Similarly when $2\sigma/(\kappa f)$ is large compared with unity the effect of the dielectric constant is unimportant in determining the flow of current.

It will be evident from such considerations that in order to ascertain the effect of soil upon alternating currents flowing therein, whether applied direct or whether resulting from the passage of electric waves through or over it, it will be necessary to have a knowledge of the two quantities κ and σ at the frequency of the currents in question.

In the publications of previous writers there is some divergence of opinion as to whether the conductivity is more conveniently expressed in electrostatic or electromagnetic units, or as the reciprocal of a resistivity in ohm-cm (i.e. ohms per cm cube). In the author's opinion the procedure to adopt is that of expressing σ in electrostatic units, when the quantity may be substituted directly into any equations (such as those given above) involving κ or κ', which are almost invariably expressed in electrostatic units. If electromagnetic units are employed for σ, it is necessary to use a conversion factor for the ratio of the units (c^2), which introduces an unnecessary quantity into all the formulæ involved. In order to facilitate the conversion of the quantities in the mind of the reader, the following relations are given, assuming the velocity of light to be given by $c = 3 \times 10^{10}$ cm per sec.:—

$$\sigma_{e.s.u.} = \sigma_{e.m.u.} \times 9 \times 10^{20}$$
$$\sigma_{e.s.u.} = (1/\rho) \times 9 \times 10^{11}$$

where ρ is the resistivity in ohms per cm cube.

(2) PREVIOUS WORK ON THE ELECTRICAL PROPERTIES OF SOIL.

(*a*) *Early Investigations.*

Much pioneer work in the study of the transmission of electric waves over or through a conducting dielectric was included in the classical researches of Clerk Maxwell, Oliver Heaviside, and Sir J. J. Thomson. After it had been demonstrated that electric waves could be transmitted to appreciable distances over the earth's surface,

attention was devoted by several investigators to the effect of the earth in wireless communication. Sir Oliver Lodge,* in 1899, demonstrated the application of classical electromagnetic theory to this problem, while Brylinsky† and W. Burstyn‡ later studied the penetration of alternating currents into soil and sea-water. Confirmation of the fact that the earth played a part in the propagation of wireless waves was provided by the experiments of J. S. Sachs§ in 1905, who found that the radiation from a transmitter increased as the aerial was raised above the earth's surface.

A mathematical investigation of the propagation of electric waves along the earth's surface was published by A. Sommerfeld‖ in 1909, and this paper still remains the most complete theoretical treatment of the subject. In order to reduce Sommerfeld's formulæ to numerical quantities, attempts were made to obtain measurements of the conductivity of soil materials at audio frequencies by several workers, notably H. Lowy¶ and K. Uller** in 1911. Some measurements made by Eickhoff are also contained in J. Zenneck's paper†† on the propagation of waves along the earth's surface. Eickhoff studied the variation of conductivity with moisture content and found that for garden soil the value rose from $0{\cdot}5 \times 10^6$ to $1{\cdot}5 \times 10^8$ e.s.u. (electrostatic units) as the moisture content was increased from 3 to 17 per cent. In most of these cases, however, the conductivity measurements were made on artificially treated specimens of soil, and investigations carried out during the past 10 years have shown that these results are of little practical significance in radio technique at the present time. The values obtained were, however, quoted in textbooks until comparatively recently, and they have formed the basis of several investigations of the shape of the electric field in a wave transmitted along the earth's surface, e.g. those of J. Zenneck‡‡ and F. Hack.§§

(*b*) *Direct Measurement of Electrical Constants at High and Low Frequencies.*

Probably the simplest method of ascertaining the conductivity of a material is to measure the current which flows under the application of a given voltage. When a direct-current voltage is applied to a specimen of soil in this manner, the effects obtained are complicated by the occurrence of polarization phenomena giving rise to reverse electromotive forces. These effects arise from the fact that the conduction is partly electrolytic in nature owing to the moisture content of the soil. For this reason measurements of soil conductivity obtained by the application of direct current are not likely to yield reliable results suitable for use in connection with alternating currents of high frequency.

With a view to overcoming this difficulty, while still retaining the use of a d.c. generator and measuring instrument, O. H. Gish and W. J. Rooney‖‖ have used a commutator giving 60 reversals per sec. to convert the direct current into alternating current before its application to the soil, at the same time including a second commutator to act as a mechanical rectifier in the detector circuit to restore the alternating current to direct current. The subject was studied chiefly from a geological-survey standpoint, and the results obtained give values of the average resistivity of the ground to depths varying from 1 or 2 down to several hundred metres. The measurements carried out at Watheroo, Western Australia,* show that beneath a surface of high-resistivity sand ($\sigma < 10^6$ e.s.u.) there is a region of unusually high conductivity, the average value of which to a depth of 100 metres is about 13×10^8 e.s.u., decreasing to an average of $1{\cdot}4 \times 10^8$ e.s.u. for a depth of 600 metres. G. F. Tagg† has described the application of this arrangement to a megger-type earth-tester, together with results obtained in this country in a geophysical survey of earth resistivity. At the frequency of 50 cycles per sec. used in this investigation the average value of the conductivity of the surface soil for a site in Southern England was about $0{\cdot}5 \times 10^8$ e.s.u., equivalent to a resistivity of nearly 18 000 ohm-cm. Experimental measurements made for depths of a few hundred feet gave considerable variation of the conductivity with depth and the nature of the subsoil.

An alternative method of deducing the conductivity of the ground at power and telephonic frequencies is based upon a measurement of the impedance of two earthed circuits. Some recent results obtained in this manner have been recorded by J. Collard,‡ and these show that at a frequency of 3 000 cycles per sec. the effective conductivity was 36×10^8 e.s.u. at one site on the English coast, and $1{\cdot}5 \times 10^8$ e.s.u. at two other sites, one of which was inland.

In a more comprehensive investigation P. J. Higgs§ has studied the conductivity of surface soil in the neighbourhood of the National Physical Laboratory (N.P.L.) by direct measurement with alternating current of a frequency of 50 cycles per sec. Under conditions of normal temperature and moisture content for surface soil, Higgs gives a conductivity value of the order of $0{\cdot}75 \times 10^8$ e.s.u. (resistivity = 12 000 ohm-cm), the lower sandy soil at a depth of about 2 ft. having about twice this conductivity. His results show also that the conductivity increases with the temperature, the coefficient being about 3 per cent per deg. C. This is consistent with the idea that the conductivity of moist soil is electrolytic in nature.

A description of some direct measurements of the electrical properties of soil carried out at radio frequencies was published by J. A. Ratcliffe and F. G. W. White‖ in 1930. In this case the soil under examination formed the dielectric between the plates of a cylindrical condenser, and the effective capacitance and resistance of this condenser were measured at various radio frequencies up to about 4 million cycles per sec. The values of apparent dielectric constant for samples of soil from two different sites (Cambridge and Daventry) in England decreased from over 40 at a frequency of 200 kilocycles per sec. to about 12 at 3 000 kilocycles per sec. The conductivity results given by Ratcliffe and White show an erratic variation with frequency, but they lie between limiting values of about $0{\cdot}2 \times 10^8$ and $0{\cdot}5 \times 10^8$ e.s.u. for the same samples of soil. These samples were taken from the surface and were presumably of normal moisture content. On drying them out,

* See Reference (1). † *Ibid.*, (2). ‡ *Ibid.*, (3). *§ *Ibid.*, (4).
‖ *Ibid.*, (5). ¶ *Ibid.*, (6). ** *Ibid.*, (7). †† *Ibid.*, (8).
‡‡ *Ibid.*, (8). §§ *Ibid.*, (9). ‖‖ *Ibid.*, (10), (11), and (12).

* See Reference (12). † *Ibid.*, (13).
‡ *Ibid.*, (14). § *Ibid.*, (15). ‖ *Ibid.*, (16).

it was found that the dielectric constant and conductivity had decreased to about 5 and $0{\cdot}5 \times 10^6$ e.s.u. respectively.

More recently, M. J. O. Strutt* has also studied the conductivity of soil by direct observation of the current flowing through a " soil condenser " under the application of a given voltage. Over a range of frequencies of from 20 to 500 000 cycles per sec. the conductivity of surface field soil (presumably from Eindhoven, Holland), increased from $0{\cdot}33 \times 10^8$ to $0{\cdot}44 \times 10^8$ e.s.u.

A laboratory method in which a condenser containing a sample of soil is matched with an equivalent electrical circuit comprising a condenser and shunt resistance, both variable, has been employed by C. B. Feldman† at wavelengths between 8 and 32 metres (frequencies 37·5 and 9·4 megacycles per sec.). A gold-plated concentric-cylinder type of condenser was used having a capacitance—with air as the dielectric—of 15 $\mu\mu$F. To simulate the natural degree of compactness of earth, a sampling cup was used to remove from the natural state an amount just sufficient to fill the cell. For a site at Holmdel, New Jersey, U.S.A., the topsoil, consisting of black loam, showed a conductivity of from $0{\cdot}8 \times 10^8$ to $1{\cdot}5 \times 10^8$ e.s.u., the corresponding dielectric constant varying from 12 to 23. The higher values in each case were obtained when the soil was " very wet." For the clay subsoil found at a depth of 3 ft., somewhat higher values ($1{\cdot}9 \times 10^8$ and 28 respectively) were obtained. At the Netcong, New Jersey, site, where the soil to a depth of $1\frac{1}{2}$ ft. comprised dry clay with stone chips, the conductivity ranged from $0{\cdot}1 \times 10^8$ to $0{\cdot}3 \times 10^8$ e.s.u. and the dielectric constant from 7 to 10. Most of the measurements at each site showed an increase of conductivity, of the order of 10 per cent, as the wavelength was reduced from 32 to 8 metres, while the dielectric constant indicated a somewhat larger decrease with reduction of wavelength. No records of moisture content or of temperature appear to have been made in connection with these measurements, although, as will be seen later in this paper, both these factors are of importance in the carrying-out of accurate measurements of soil constants.

(c) *Measurements at Radio Frequencies by Wave-Tilt Methods.*

Among the earliest methods employed at radio frequencies to determine an effective practical value for the conductivity of soil was that of the tilting-rod aerial, used by R. H. Barfield and the present author‡ in some measurements carried out in 1924. When electric waves are propagated over the surface of a perfect conductor the electric force is always at right angles to the surface. In the case of imperfect conductivity, however, the electric force is subjected to a forward tilt from the normal position, and when both the dielectric constant and the conductivity are of importance the electric field is of the form of a rotating vector terminating in an elliptical locus in the plane of propagation of the wave. The angle of forward tilt of the electric field or of the major axis of the ellipse can be measured with a suitable rotating aerial system.

In an experimental survey carried out over a large portion of Southern England with the aid of this method, the conductivities varied from $0{\cdot}6 \times 10^8$ to $4{\cdot}7 \times 10^8$ e.s.u., but no consistent correlation was found between this value and the frequency or the nature and condition of the soil at the site of the measurements. Later measurements* carried out at one site (Radio Research Station, Slough) over a period of several months gave a mean value of $0{\cdot}9 \times 10^8$ e.s.u. for the conductivity at frequencies from 620 to 860 kilocycles per sec. More recently, R. H. Barfield and G. H. Munro† have used the same method at a frequency of 19 megacycles per sec. (wavelength 16 m), and at a site in the neighbourhood of Slough the resulting conductivity values ranged from $0{\cdot}5 \times 10^8$ to $2{\cdot}5 \times 10^8$ e.s.u.

The tilting-rod method has also been applied by Cairns‡ in Western Australia at the site previously used by Gish and Rooney,§ and from the results obtained he confirmed the deduction that the highly conducting subsoil was effective in determining the mode of propagation of radio waves in spite of the low conductivity of the surface sand.

An alternative method of arriving at values of earth conductivity from the tilt of the wave-front is provided by the use of the wave antenna, which has been developed in America and in this country for obtaining highly directive reception in long-distance communication. This antenna derives its signal e.m.f. from the horizontal component of the electric force in the arriving wave, and by comparing this e.m.f. with that obtained on a vertical aerial or closed loop a direct comparison may be made between the horizontal and vertical components of electric force in the arriving wave-front. In this manner‖ values of the conductivity of the ground have been deduced for Wroughton in Southern England and Cupar in Scotland as $2{\cdot}5 \times 10^8$ and $1{\cdot}0 \times 10^8$ e.s.u respectively, while at Houlton, Maine, U.S.A., a value of $0{\cdot}14 \times 10^8$ e.s.u. was obtained. In each case the frequency employed was 60 kilocycles per sec.

One of the outstanding advantages of the wave-tilt method of conductivity determination described in this section, is that it gives the effective value of the constants for the earth at the site of the measurements. The varying contributions of the layers of soil of different depths are correctly integrated for the frequency employed, and the results obtained are thus directly applicable to the practical case for which the data are required. Laboratory measurements on isolated samples can be carried out to a higher degree of accuracy, but it is necessary to take account of possible variations with depth before practical application of the results can be made. This matter is discussed further in Section (6).

(d) *Evaluation of Conductivity from Field-Attenuation Measurements.*

When electric waves are radiated from a transmitting station the intensity of the field at any point is a function of the distance of the point from the source, the wavelength or frequency employed, and the electrical constants of the earth. Various theoretical and empirical

* See Reference (17). † *Ibid.*, (18). ‡ *Ibid.*, (19).

* See Reference (20). † *Ibid.*, (21).
‡ *Ibid.*, (22). § *Ibid.*, (10). ‖ *Ibid.*, (23).

laws have been given from time to time connecting the field intensity with the distance of transmission, and of these the most comprehensive theoretical analysis was that given by Sommerfeld* in 1909.

On the experimental side Ratcliffe and Barnett† measured field-attenuation curves for wave-frequencies of 190 and 830 kilocycles per sec., and, by a comparison with similar curves calculated from Sommerfeld's theory, conductivity values of $1 \cdot 6 \times 10^8$ and $0 \cdot 5 \times 10^8$ e.s.u. respectively were obtained for the above frequencies. Barfield‡ in 1926 measured attenuation curves at distances up to 150 km in various directions radiating from one of the London broadcasting stations at a carrier-wave frequency of 825 kilocycles per sec., and obtained values of the earth's conductivity ranging from $0 \cdot 2 \times 10^8$ to $1 \cdot 0 \times 10^8$ e.s.u. From subsidiary experiments, Barfield concluded that the differences in conductivity in different directions were due to the varying densities of trees in the paths of transmission. These investigations were continued by G. H. Munro§ for the higher frequency of 12 megacycles per sec. (wavelength 24 metres), and conductivity values of from $0 \cdot 8 \times 10^8$ to 3×10^8 e.s.u. were deduced for ground in the vicinity of Slough.

The two great disadvantages of these attenuation methods of deriving values of the earth's electrical constants are, first, that the method employed rests upon an assumed theory of the process of attenuation; and secondly, that only an average value can be obtained for the soil covering the whole path of transmission. As far as the first point is concerned, it is only comparatively recently that it has been generally agreed that Sommerfeld's theory, already referred to, covers the case of the propagation of waves along the earth's surface, although modifications to this theory have been suggested by B. Rolf.‖ Using this modified theory, Rolf has deduced values of the electrical constants of soil in various parts of Sweden from field-strength measurements made by Lemoine. Around the Motala and Karlsborg stations working at frequencies of about 230 kilocycles per sec. (wavelength 1 300 metres), the conductivity is low, varying from $0 \cdot 05 \times 10^8$ to $0 \cdot 09 \times 10^8$ e.s.u., the corresponding dielectric constant being 15. Around Malmo, and for frequencies of about 1 000 kilocycles per sec., the conductivity is about $1 \cdot 3 \times 10^8$ e.s.u. while the dielectric constant is 10.

Rolf's calculations from Sommerfeld's analysis have also been used by S. S. Kirby and R. A. Norton¶ in connection with field-attenuation measurements which they have conducted on various transmitting stations in America. For wave-frequencies between 600 and 1 000 kilocycles per sec. the deduced values of earth conductivity ranged from $0 \cdot 3 \times 10^8$ to $1 \cdot 0 \times 10^8$ e.s.u., the average value of the dielectric constant being 13. While some little experimental evidence has been put forward in favour of Rolf's modification, it is considered that values of the electrical constants of the earth should preferably be obtained in other ways and then used for insertion in the appropriate formulæ to check the theoretical analysis against experimental attenuation curves.

* See Reference (5). † *Ibid.*, (24). ‡ *Ibid.*, (25).
§ *Ibid.*, (21). ‖ *Ibid.*, (26). ¶ *Ibid.*, (27).

In the course of an investigation of the field intensities around some Australian broadcasting stations, R. O. Cherry* has been able to estimate the effective conductivity of the ground over which his experiments were carried out. His results for the case of Melbourne on a carrier-wave frequency of 810 kilocycles per sec. gave a conductivity of $3 \cdot 6 \times 10^8$ e.s.u. in a south-westerly direction over bare ground with few trees; in a south-easterly direction, where the ground is covered with low scrub and light timber, the value was $3 \cdot 0 \times 10^8$ e.s.u.; while in the northerly direction, where the ground is heavily timbered, a lower value of about $0 \cdot 9 \times 10^8$ e.s.u. was obtained. This decrease in effective conductivity with increase in the density of trees is in good agreement with Barfield's results obtained in England and referred to above. The results obtained by Cherry around Hobart, Tasmania, at 580 kilocycles per sec. indicated a bare-ground conductivity of $0 \cdot 45 \times 10^8$ e.s.u.

(e) Miscellaneous Results at Ultra-Short Wavelengths.

In the investigations described in the preceding sections the maximum frequency employed was in the neighbourhood of 10 000 kilocycles per sec., while the majority of the measurements were carried out at 1 000 kilocycles per sec. or less. The resulting value of the conductivity obtained for various sites in this country has been found to be of the order of 10^8 e.s.u. For this conductivity the quantity $2\sigma/f$ is equal to 200 at a frequency of 1 000 kilocycles per sec., and from the reasoning given in Section (2) it will be evident that unless the dielectric constant κ has a value approaching 100, the value of $2\sigma/(\kappa f)$ will be so high that κ will play only a negligible part in the propagation of waves over or through the earth medium. If the value of σ is found to be independent of the frequency f, then as f is increased the value of $2\sigma/f$ will decrease; so that it might be expected that at a sufficiently high frequency the dielectric constant would play a prominent, and even a major, part in determining the effect of the earth on wave propagation. This fact, in conjunction with the modern widespread use of short waves for communication purposes, adds considerable interest and importance to the study of the earth's electrical properties at very high radio frequencies.

M. J. O. Strutt† has made soil-conductivity determinations (in Holland) at various frequencies between $0 \cdot 5 \times 10^6$ and 20×10^6 cycles per sec. by measuring the attenuation along two parallel wires, 100 metres in length, buried in the ground 2 cm apart at a depth of 30 cm. It was found that the amplitude of the waves on the wires decreased according to an exponential law, which indicated a conductivity of $0 \cdot 45 \times 10^8$ e.s.u. and a dielectric constant of 10.

In the course of an investigation of the influence of the earth on the radiation from an antenna, Strutt‡ also developed a method of measuring the conductivity of the earth, based upon radiation measurements made with elevated transmitting and receiving apparatus. Using a wavelength of 1·4 metres (frequency 210 megacycles per sec.), a value of conductivity in excess of 10×10^8 e.s.u. was obtained for soil which at lower

* See Reference (28). † *Ibid.*, (17). ‡ *Ibid.*, (29).

frequencies possessed a normal value of about 1×10^8 e.s.u.

During the past two or three years J. S. McPetrie and the author have investigated the attenuation of ultra-short waves when transmitted along the earth's surface, largely with the object of obtaining more definite knowledge of the electrical constants of the earth at very high radio frequencies. In the first experiments* a series of field-attenuation measurements were made for frequencies between 30 and 60 megacycles per sec. (wavelengths 10 to 5 metres), and these indicated that the value of the conductivity of field soil at Teddington lies between 5×10^8 and 30×10^8 e.s.u. for the above frequencies. A later paper† describes the extension of this work to a frequency of 190 megacycles per sec. (wavelength 1·6 metres). At this short wavelength the type of attenuation curve obtained depends to a large extent upon the height of the transmitting and receiving apparatus above the surface of the earth, interference effects being obtained in a manner similar to that described by Strutt.‡ Comparisons between experimental and theoretical attenuation curves suggested in this case an effective conductivity value of about 95×10^8 e.s.u. for the same site as that used in the previous measurements.

While these values at very high frequencies must be regarded as somewhat tentative pending confirmation by further experiments, one important point has already emerged. Owing to the considerable rise in the value of the conductivity with increase of frequency the experimental methods do not enable the dielectric constant of the earth to be ascertained with any great accuracy, although a value of about 10 appears to fit the results. This is due to the fact that the value of $\kappa f/(2\sigma)$ is about 0·1 at the highest frequency employed, so that, as previously explained, the dielectric constant plays an almost negligible part in determining the flow of current in the earth or the propagation of waves over its surface.

(3) Measurement of the Electrical Properties of Soil by a Laboratory Method.

The survey of published work given in the previous section shows that in certain rather scattered frequency-ranges and for various localities, measurements of the electrical properties of soil have been made chiefly by field methods depending upon wave-propagation phenomena, and in a few cases only by laboratory methods. It was considered desirable to obtain more complete information on this subject in a systematic manner under controlled conditions, taking full advantage of the improved facilities and technique now available in the radio laboratory. In a recent paper§ the author described the application of a method of measuring resistance and reactance at radio frequencies to a preliminary study of the electrical conductivity of soil. Sufficient results were there given to show that these were substantially in agreement with such previous measurements as had actually been carried out in the field upon electric waves. In the present paper the application of this method is examined in more detail, and the investigation has been extended to the general survey of the electrical properties of the soil from a number of different sites in this country. Although interest in this matter has arisen directly from its association with radio communication, and the majority of the work was carried out at frequencies between 100 and 10 000 kilocycles per sec., the measurements have in some cases been extended through the audible range down to a power frequency of 50 cycles per sec.

The basic principle of the method employed in this work consisted in measuring the constants, capacitance, and resistance, of a fixed condenser of suitable size and shape, having for its dielectric the sample of soil under examination. From the measured values of these constants and a knowledge of the capacitance of the condenser, with air as the dielectric, the effective conductivity and dielectric constant of the soil can be calculated as follows. If C_a is the capacitance of the condenser in air, and C_s and R_s are the capacitance and shunt resistance respectively of the condenser when it is filled with soil, then the apparent dielectric constant is given by

$$\kappa = C_s/C_a \quad . \quad . \quad . \quad . \quad . \quad (2)$$

while the conductivity (σ) or resistivity (ρ) can be found from the relationship:—

$$\sigma = 1/\rho = 1/(4\pi C_a R_s) \quad . \quad . \quad . \quad . \quad (3)$$

Equation (2) gives the dielectric constant in electrostatic units. In equation (3), R_s is usually measured in ohms, and then, if C_a is measured in centimetres, ρ will be given in ohms per cm cube, or, more briefly, in ohm-cm. To obtain the conductivity in electrostatic units, the relationship $\sigma_{e.s.u.} = 9 \times 10^{11}/\rho$ may be employed.

At radio frequencies the measurements of resistance and reactance were carried out by the general method described by F. M. Colebrook and R. M. Wilmotte,* in the manner adopted in the work to which reference has already been made. For the lower frequencies a standard type of capacitance bridge was employed, using a telephone as the detector in the audible range and a vibration galvanometer at the power frequency of 50 cycles per sec.

(4) Measurements on Soil Indicating the Influence of Various Factors.

(a) *Practical Details.*

At the beginning of the investigation some experiments were carried out to determine the most suitable size and shape of container for the work. Consistent results were obtained for tightly rammed soil in cylindrical containers of various dimensions; and as in this condition the density of the soil in the container was found to correspond to the density of the soil just below the surface of the undisturbed grass meadow from which the sample was taken, this was assumed to be the desirable condition for the soil under test. While there was no reason to suppose that the material of the electrodes affected the results, the final containers employed were made of copper with keramot insulation. The capacitance of the container used for finely powdered

* See Reference (30). † *Ibid.*, (31). ‡ *Ibid.*, (29). § *Ibid.*, (32).

* See Reference (33).

sand or loam was 2·5 $\mu\mu$F, while a larger container (used for coarse gravel, etc.) had a capacitance of 3·2 $\mu\mu$F. It was found that repeated measurements on successive samples of soil from the same site and used under the above conditions gave consistent results to an accuracy of 10 per cent or less; in view of the relatively large variation of the electrical properties of the soil with its nature, moisture content, and temperature, as described below, this overall accuracy was considered to be quite adequate for all purposes for which the information was required. Experiments made from time to time in the course of the work showed that the measured quantities

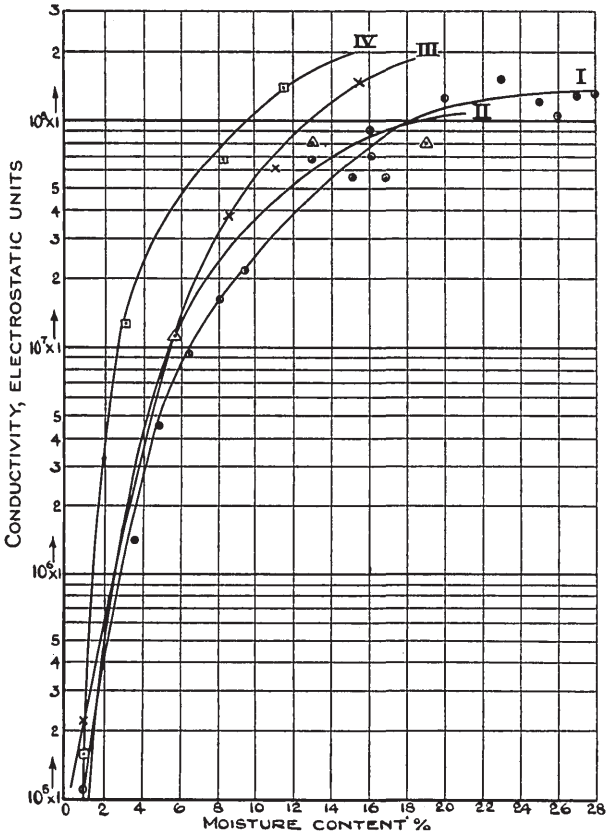

FIG. 1.—Relation between conductivity and moisture content for soils from sites Nos. I to IV (N.P.L.) at a frequency of 1 200 kilocycles per sec.

are independent of the applied voltage over a range of from 0·1 to 1·0; the majority of the measurements discussed below were made with a potential difference of about 0·5 volt across the condenser.

(b) Dependence of Electrical Properties on Moisture Content.

In a previous paper it was shown that the electrical properties of soil and their variation with frequency depend upon the moisture content* of the specimen under examination. For example, Fig. 1 illustrates a set of conductivity measurements made at a frequency of 1 200 kilocycles per sec. on samples of garden loam and field soil from four different sites within the N.P.L. It is seen that the conductivity of the dry soil is of the order of 10^5 e.s.u. (9 megohms per cm cube), while at a moisture content of between 12 and 26 per cent the conductivity approaches a limiting value of between 10^8 and 2×10^8 e.s.u. (9 000 to 4 500 ohms per cm cube). The corresponding values of dielectric constant are shown in Fig. 2, from which it is seen that the value is 3 or 4 for the dry soil, rising to 30 or 40 for the very moist soil. It is worthy of note that the limiting values to which the curves in Figs. 1 and 2 approach, are for moisture contents which may be termed normal values for the soil in question. For example, in the case of site 1

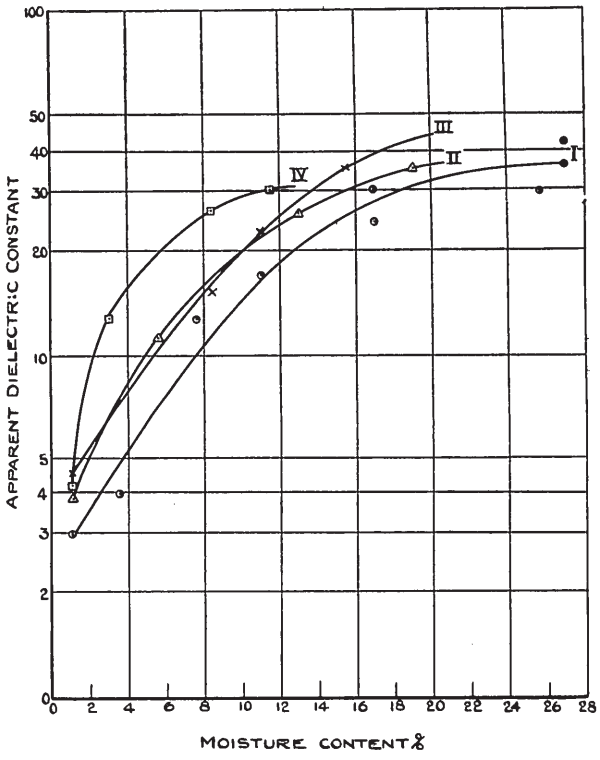

FIG. 2.—Relation between apparent dielectric constant and moisture content for soils from Sites Nos. I to IV (N.P.L.) at a frequency of 1 200 kilocycles per sec.

at the N.P.L. the moisture content of the surface soil was measured every day over a period of 12 months, and was found to lie between 16 and 30 per cent over the greater part of the year. It was only during periods of heavy rain that the upper limit was exceeded, and, while a few samples having a content of 39 per cent were on occasions taken while it was raining, the value rapidly decreased to 30 per cent when the rain stopped. In the other direction the moisture in the surface soil decreased steadily during the dry summer season, but it was only after several weeks of hot dry weather that the moisture content reached its lower limit of 4 per cent. This condition, however, prevailed for only a few inches below the surface. Samples taken during this period from a depth of 1 ft. gave a minimum moisture-content value of 16 per cent.

* In this work, the moisture content was determined by placing a weighed sample of soil for 24 hours in an electric oven, the temperature of which was maintained at just over 100° C. The loss of weight was taken to be that of the moisture originally contained in the sample, and the ratio of this to the weight of the dry soil is given as the percentage moisture content.

This retention of the moisture at a short distance below the surface indicates that as the surface soil dries out there will not necessarily be any marked effect on wave propagation. For, as the surface soil dries out, the depth of penetration of the electric waves will increase slightly into the more moist, and thus better-conducting, subsoil; and this factor will tend to counteract appreciably the effect of any departure of the moisture content of the soil from its normal value on the waves travelling along its surface.

(c) *Effect of Frequency on Electrical Properties.*

The effect on the electrical properties of soil of varying the frequency was found to depend upon the moisture content. For example, in the case of the soil from site I referred to above, when the moisture was reduced to less than 1 per cent by artificial drying, the conductivity increased from about 10^5 e.s.u. at a frequency of 1 000 kilocycles per sec. to about 9 times this value at 10 000 kilocycles per sec. As the moisture content is increased this variation with frequency diminishes considerably, although it is still perceptible for moist soil at the higher frequencies. The dielectric constant behaves in a different manner. At low moisture-contents there is practically no variation of the value with frequency, while at a normal moisture-content of about 26 per cent the dielectric constant decreases from about 90 at 100 kilocycles per sec. to 25 at 10 000 kilocycles per sec.

In order to explore this matter further, a few samples of soil were subjected to measurement over a frequency range which was extended in the lower direction to 50 cycles per sec. The result of such a typical series of measurements is illustrated in Fig. 3. It is seen that for frequencies below 1 000 kilocycles per sec. the conductivity does not vary appreciably, and the value obtained at 50 cycles per sec. agrees with that previously obtained by Higgs* for soil at the N.P.L. At a frequency above 1 000 kilocycles per sec. there is a slight rise in the conductivity, which lends some confirmation to the high values experienced during field measurements at the N.P.L. on ultra-short wavelengths.† Over the same range the dielectric constant appears to attain the very high value of 100 000 at a frequency of 50 cycles per sec., decreasing continuously to a value of about 30 at 10 000 kilocycles per sec.

Such apparently abnormal values of the dielectric constant have been previously experienced in the study of solid dielectrics, more particularly with electrolytes, and the effects have been interpreted as being caused by the formation of a polarization film of molecular thick-

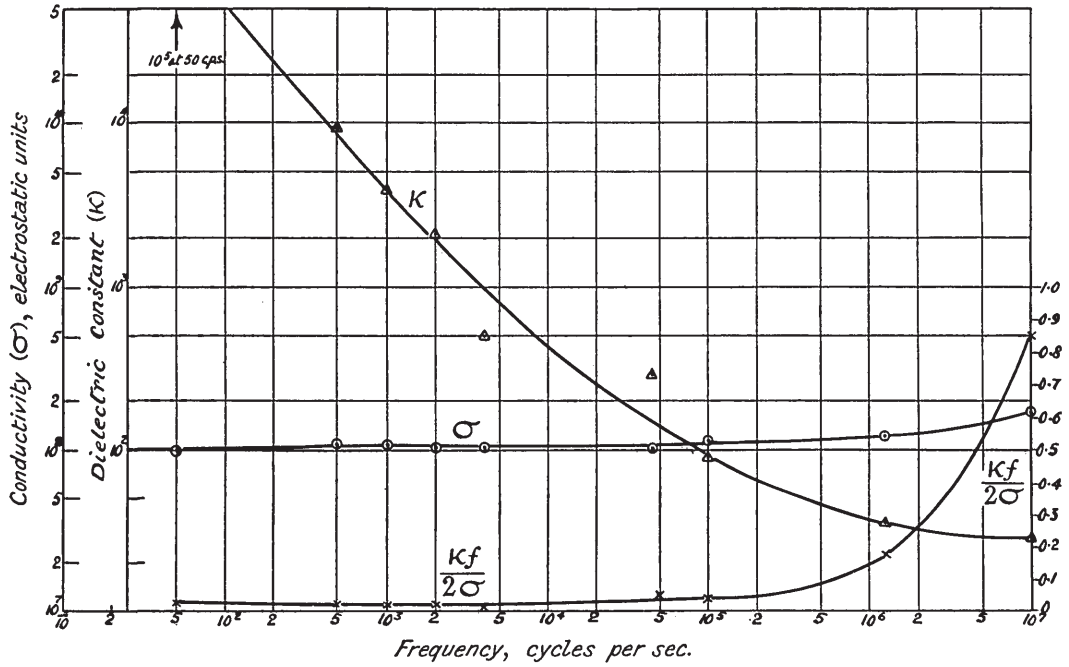

FIG. 3.—Results of laboratory measurements of electrical properties of surface soil from N.P.L. (Site No. I) at frequencies between 50 and 10^7 cycles per sec. Moisture content, 25 per cent.

ness over the surface of the electrodes.‡ This suggestion was recently explored in connection with a study of the electrical properties of sea water,§ and was found to be useful in indicating that the true dielectric constant of this electrolyte is probably about 80, although the apparent values as measured ranged up to several million at audio frequencies. In the case of the soil measurements the method of treatment based upon the above suggestion was not found to give similar results for the evaluation of the true dielectric constant. A notable point of difference between the two cases is that for soil the measured values of the dielectric constant appeared to be independent of the dimensions of the container to a large extent, whereas for the sea water the apparent value varied in a ratio of 2 or 3 to 1 for different lengths of container. In the soil case, any polarization phenomena are likely to be complicated

* See Reference (15). † *Ibid.*, (30). ‡ *Ibid.*, (34). § *Ibid.*, (35).

by the inherent granular structure of the material, which may thus only loosely be regarded as similar in behaviour to an electrolyte.

The extent to which the dielectric constant in comparison with the conductivity plays a part in determining the flow of an alternating current, depends upon the value of the quantity $\kappa f/(2\sigma)$, as already explained. Now in Fig. 3 the lowest curve gives the value of this quantity over the whole range of frequencies examined. It is seen that, even with the very high values of dielectric constant measured at the lower frequencies, the above quantity is less than 0·1 for all frequencies below 1 000 kilocycles per sec. It is thus evident that the dielectric constant plays only a small, if not negligible, part in the determination of current flow in soil over this range of frequencies, and for this reason it was not considered expedient to pursue the study of the matter further at this stage. For the same reason the measurement of

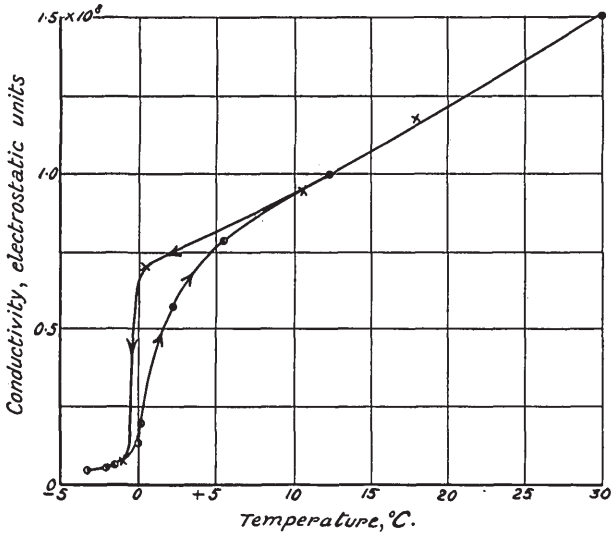

FIG. 4.—Variation of conductivity with temperature of normal sample of soil from Site No. I (N.P.L.).
Frequency = 1 200 kilocycles per sec.

the dielectric constant is much more difficult than that of the conductivity, and the accuracy of the results discussed above is not considered to be high. As the frequency increases from 1 000 to 10 000 kilocycles per sec., however, the value of $\kappa f/(2\sigma)$ is seen to increase to values of the order of unity, and it is therefore in this region—and possibly at higher frequencies—that the matter requires further study.

(d) Effect of Temperature on Soil Constants.

In the course of his work at a frequency of 50 cycles per sec., Higgs* measured the conductivity of the soil at temperatures between − 15° C. and + 20° C. With a view to ascertaining the corresponding values at radio frequencies a sample of the loam from site I at the N.P.L. was subjected to a temperature variation from − 3° to + 30° C., while the electrical measurements were made at a frequency of 1 200 kilocycles per sec. The results obtained in this case are shown in Figs. 4 and 5, which refer to the conductivity and dielectric constant respectively. These diagrams show very clearly the sudden change in the values of these constants which occurs as the temperature passes through the freezing point of water. In the case of the conductivity curve (Fig. 4) the temperature at which the change takes place appears to depend somewhat upon the direction of the temperature-change. Although precautions were taken to ensure uniformity of temperature throughout the sample at the time the measurements were made, it is just possible that this effect was due to excessive lag in the attainment of thermal equilibrium. Over the straight part of the curve, between temperatures of 5° and 30° C., the mean temperature coefficient is 2·3 per cent per deg. C., referred to the value at 20° C. Turning to Fig. 5, it is seen that while the dielectric constant appears to be reasonably independent of temperature over the range 1° to 20° C., there is a sudden change in the neighbourhood of the freezing point, where the value drops from about 45 at + 1° C. to 14 at − 3° C.

In considering this curve it is interesting to observe

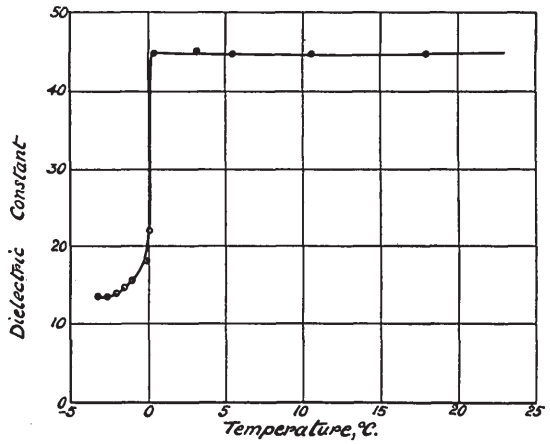

FIG. 5.—Variation of dielectric constant with temperature of normal sample of soil from Site No. I (N.P.L.).
Frequency = 1 200 kilocycles per sec.

that while the dielectric constant of pure water is nearly 80 at all frequencies up to at least 150 million cycles per sec., the value for ice is only about 4. An experimental check of this sudden change on passing through the freezing point was carried out in connection with the present investigation, the frequency employed being 1 200 kilocycles per sec.

During the course of the experimental measurements described in Section (5) below, the temperature coefficient was measured for a few other samples of different types of soil, also at a frequency of 1 200 kilocycles per sec. The results obtained are given in Table 1, which includes the results for the N.P.L. sample referred to above.

It will be seen from these typical measurements that the temperature coefficients of conductivity of different types of soil lie within the range 2–2·5 per cent per deg. C. Since the normal seasonal variation of ground temperature in this country is over 30 deg. C., it will be appreciated that temperature variation alone can account for

* See Reference (15).

a change in conductivity of the open ground approaching 100 per cent. In this connection, as with the moisture-content case referred to above, it must be remembered that the surface variations are not completely followed by the temperature of the ground below the surface, and that the variation of the effective conductivity of the ground with surface temperature will depend upon the depth to which the electric waves penetrate the earth. Measurements of thermal variation with depth have shown that while a diurnal variation of 20 deg. C. at the surface produces a change of only 1·4 deg. C. at about 1 ft., a seasonal change of 30 deg. C. at the surface produces a variation of about 20 deg. C. at a depth of 3 ft., and of 0·3 deg. C. at about 30 ft. It is likely that the effective depth of soil involved in wave propagation is only a few feet, particularly in the case of short wavelengths, and this being so the seasonal variation of temperature and the consequent change in conductivity will be fairly large. In view of this uncontrollable condition which is involved in the transmission of electric waves, it is considered that the limitation of accuracy of the measurements described in this paper to the order of 10 per cent is not of serious importance in the application of results to practical communication.

TABLE 1.

Temperature Coefficients of Conductivity of Various Types of Soils.

Site	Type of soil	Conductivity (in e.s.u.) at 20° C.	Temperature coefficient of conductivity at 20° C.
			per cent per deg. C.
N.P.L. ..	Sandy loam	1·2	2·3
Daventry ..	Brown sand	0·11	2·2
Dousland ..	Dark brown loam	0·26 × 10^8	2·1
Washford Cross	Red-brown clay	3·1	2·3

(5) AN ELECTRICAL SURVEY OF THE SOIL IN DIFFERENT PARTS OF GREAT BRITAIN.

(a) *Scope and Method of Investigation.*

With the co-operation of the British Broadcasting Corporation and the Post Office, the author has been able to investigate the electrical properties of samples of soil obtained from 12 different sites in England and Scotland. This study was not limited to the surface soil, as samples were obtained from each site at various depths down to 10 ft.; while at the Midland Regional Station site, near Droitwich, the opportunity was provided of obtaining samples at greater depths down to 300 ft. As each sample of soil was taken out at the site it was sealed up in a glass jar and despatched to Teddington. Only two or three samples per day were sent in this manner, so that there was no undue delay in carrying out the measurements. Furthermore, the excavation to the required depth was arranged in correct daily amounts so as to minimize the effects of exposure of the subsoil at the actual site. When the samples comprised loose soil, sand, or clay, suitable for packing in the measuring condenser, the moisture content was determined immediately after their receipt at the Laboratory. On the same day the electrical measurements were carried out at frequencies of 1, 100, 1 200, and 10 000 kilocycles per sec. In cases where the subsoil comprised solid materials, such as slate or granite, these were machined into small slabs, and sheets of tinfoil were affixed to opposite faces to form electrodes for measurement purposes.

The samples from the Post Office stations were measured during August and September, 1932, and those from the majority of the B.B.C. stations during October and November, 1932, while the samples from the 300-ft. bore at Droitwich were obtained during February and March, 1933. To complete the series of measurements, samples at depths down to 10 ft. were obtained from a site at the N.P.L. during January, 1933.

A summary of all the results obtained in this study is given in Table 2, which includes the geological classification of each site and a brief description of the nature of the soil obtained at each depth. The moisture content is given in the customary manner as the percentage (by weight) of water to dry soil. The majority of the measurements were made at a room temperature of from 17° to 21° C., but the conductivity measurements given in the Table have been corrected to a temperature of 20° C., using the mean coefficient of 2·3 per cent per deg. C. as determined experimentally for several samples of soil (see Section 4*c*).

(b) *Conductivity Values.*

It will be observed from Table 2 that the conductivity of surface soil at a frequency of, say, 1 200 kilocycles per sec., varies from $0{\cdot}16 \times 10^8$ at Merrivale to $4{\cdot}0 \times 10^8$ at Tatsfield. At the former site the conductivity decreases very rapidly with depth to a value of $2{\cdot}4 \times 10^5$ owing to the presence of solid granite, while at Tatsfield the conductivity varies with depth only to a minimum of $1{\cdot}6 \times 10^8$. The results of similar measurements at the above frequency for other sites lie between limiting values of $1{\cdot}6 \times 10^5$ and about 10^{10}. The conductivity of the sample definitely increases with the frequency in all cases, but the amount of the variation is considerably greater for the poorly-conducting and solid samples than for the more highly-conducting soils.

A point of some interest is the rapid change in conductivity at sites not far apart. For example, at Rugby for two sites only 20 yards apart, values of $3{\cdot}9 \times 10^8$ and $0{\cdot}70 \times 10^8$ respectively were obtained for surface samples at a frequency of 1 200 kilocycles per sec. The moisture content associated with the first site was nearly 3 times that found at the second, and was probably in part responsible for the high conductivity. Thus for surface soil of the same nature the moisture content, and hence the conductivity, may be directly dependent upon the subsoil, apart from any contribution of the subsoil to the effective conductivity at different depths. On the other hand the general conductivity at Rugby ranges from about $0{\cdot}7 \times 10^8$ to $9{\cdot}5 \times 10^8$ at the above frequency. At Daventry, about 8 miles away, the corresponding values are from $0{\cdot}1 \times 10^8$ to $1{\cdot}1 \times 10^8$.

In general it may be said that the clays show a high

TABLE 2.

Measurements of Samples of Soil taken from Different Depths at Various Sites.

Sample No.	Site	Geological classification	Depth	Description of sample	Moisture content	Conductivity (in e.s.u.) at 20° C. and at frequencies in kilocycles per sec. of :—				Apparent dielectric constant (in e.s.u.) at frequencies in kilocycles per sec. of :—	
						1	100	1 200	10 000	1 200	10 000
			ft.		per cent						
90	Rugby Radio Station (1)	Lower lias	Surface	Dark fibrous loam	60	$3{\cdot}0\times10^{8}$	$3{\cdot}4\times10^{8}$	$3{\cdot}9\times10^{8}$	$6{\cdot}0\times10^{8}$	100	55
92			1	Loam and clay	33	6·5	7·0	7·0	9·0	95	43
93			2	Clay and sand	26	7·5	8·0	8·0	12·0	105	48
94			3	Blue clay	25	8·0	9·0	9·5	11·0	95	46
95			10	Blue clay	23	6·0	6·5	7·0	8·5	60	29
97	Rugby Radio Station (2)	Lower lias	Surface	Loam	22	0·55	0·65	0·70	1·1	35	25
104			1	Loam and clay	13	0·85	0·85	1·2	1·4	32	21
105			3	Blue clay	27	6·5	7·5	8·0	13·0	125	75
106			5	Clay and sand	21	5·5	5·5	6·5	9·0	75	42
107			10	Blue clay	25	7·0	8·0	8·5	12·0	70	40
98	Baldock, Herts (P.O. Receiving Station)	Chalk	Surface	Fibrous loam	21	0·85	0·90	0·95	1·4	39	23
99			1	Chalky loam	21	0·55	0·55	0·85	0·95	41	25
100			2	Chalk	24	0·28	0·26	0·38	0·61	28	21
101			3	Chalk	27	0·65	0·70	0·80	1·0	35	29
102			5	Chalk	26	0·91	1·4	1·6	2·0	45	38
103			10	Chalk	27	1·3	1·4	1·5	1·9	44	34
108	Tatsfield, Kent (B.B.C. Receiving Station)	Upper greensand	Surface	Fibrous loam	37	2·7	3·4	4·0	5·0	80	49
109			1	Brown, sandy clay	19	2·2	2·4	2·4	3·8	39	19
110			2	Brown sand	15	1·8	2·0	2·1	3·3	33	19
111			3	Light brown sand	13	1·4	1·5	1·6	2·1	33	25
112			5	Light brown sand	20	2·3	2·3	2·5	4·0	60	37
113			10	Yellow sand	15	1·5	1·7	2·0	2·9	60	28
114	Brookmans Park, Herts (London Regional Station)	London clay	Surface	Fibrous loam	19	0·90	0·95	1·1	1·7	48	25
115			1	Stony loam	18	0·85	0·90	0·95	1·4	40	24
116			2	Light sandy clay	22	0·50	0·65	0·70	1·6	45	24
117			3	Sandy clay	22	1·1	1·2	1·5	2·9	70	33
118			5	Sandy clay	21	1·5	1·7	1·9	2·6	75	36
119			8 to 10	Clay and shingle	10	1·5	1·6	1·6	2·7	42	23

TABLE 2.—*Continued.*

Measurements of Samples of Soil taken from Different Depths at Various Sites.

Sample No.	Site	Geological classification	Depth	Description of sample	Moisture content	Conductivity (in e.s.u.) at 20° C. and at frequencies in kilocycles per sec. of :—				Apparent dielectric constant (in e.s.u.) at frequencies in kilocycles per sec. of :—	
						1	100	1 200	10 000	1200	10 000
			ft.		per cent						
121	Daventry,	Upper lias	Surface	Fibrous loam	28	$0\cdot85\times10^{8}$	$0\cdot95\times10^{8}$	$1\cdot1\times10^{8}$	$1\cdot6\times10^{8}$	48	30
122	Northants		1	Sandy loam	16	0·34	0·34	0·40	0·61	20	17
123			2	Brown sand	14	0·29	0·29	0·33	0·46	20	14
124			3	Brown sand	5·0	0·10	0·11	0·12	0·19	11	8
126			5	Sand and sandstone	8·5	0·075	0·090	0·12	0·22	14	9
125			10	Sand and sandstone	24	0·26	0·33	0·44	0·80	47	31
127	Washford Cross,	Red marls	Surface	Reddish-brown loam	23	1·5	1·7	1·8	2·3	46	32
128	Somerset (West		1	Reddish-brown clay	20	1·5	1·7	1·8	2·5	50	33
130	Regional		2	Reddish-brown clay	18	2·6	2·8	3·1	3·6	80	45
129	Station)		3	Reddish-brown clay	21	4·7	4·9	5·5	8·0	130	85
131			5	Reddish-brown clay	19	2·8	3·1	3·3	4·2	55	40
132			10	Reddish-brown clay	15	4·3	4·5	4·5	6·1	70	55
133	Brendon Hills,	Devonian	Surface	Black fibrous loam	210	1·3	1·5	1·8	2·5	90	65
134	Somerset		1	Loam and slate	9·0	0·026	0·030	0·040	0·060	12	10
135			2	Loam and slate	9·0	0·016	0·016	0·026	0·035	9·0	8·0
136			3	Loam and slate	8·0	0·0055	0·0060	0·013	0·015	7·0	6·5
137			5	Loam and slate	5·5	0·0022	0·0039	0·0085	0·016	6·0	5·5
S. 7			10	Slate	—	0·00026	0·0025	0·0092	0·046	9·5	8·0
140	Merrivale,	Granite	1	Gritty loam	18	0·12	0·12	0·16	0·18	22	15
141	Dartmoor,		2	Gritty loam	13	0·14	0·14	0·18	0·20	14	13
S. 1	Devon		3 to 10	Granite	—	0·00090	0·0070	0·028	0·11	12	8·5
S. 2			3 to 10	Granite	—	0·00070	0·0050	0·019	0·095	10·0	7·5
S. 3			3 to 10	Granite	—	0·00039	0·0021	0·011	0·050	9·5	7·5
S. 5			3 to 10	Granite	—	0·000015	0·00090	0·0024	0·015	7·0	6·5
139	Dousland,	Devonian	Surface	Loam	47	0·55	0·60	0·70	0·85	50	30
142	Dartmoor,		1	Dark brown loam	41	0·24	0·24	0·31	0·47	32	27
S. 4	Devon		Below 1	Slate	—	0·00028	0·0017	0·011	0·050	9·5	8·0
S. 6			Below 1	Granite	—	0·000030	0·00026	0·0016	0·0070	6·0	6·0

143	Moorside Edge,	Millstone	Surface	Fibrous loam	130	$1{\cdot}2\times10^8$	$1{\cdot}6\times10^8$	$1{\cdot}8\times10^8$	$3{\cdot}9\times10^8$	95	40
144	Yorks (North	grit	1	Dark grey clay	60	1·2	1·4	1·6	3·1	75	36
145	Regional		2	Dark grey clay	35	0·70	0·95	1·0	2·4	85	33
146	Station)		3	Dark grey clay	39	1·1	1·5	1·6	3·1	75	36
147			5	Dark grey clay	19	0·85	1·0	1·2	2·9	70	31
148			10	Yellow and grey clay	15	0·31	0·33	0·37	0·75	28	16
149	Westerglen,	Boulder	Surface	Fibrous loam	38	0·55	0·65	0·75	1·1	50	20
150	Falkirk (Scot-	clay	1	Fibrous loam	30	1·0	1·0	1·1	1·5	60	20
151	tish Regional		2	Clay and loam	19	1·1	1·1	1·2	1·7	60	21
152	Station)		3	Dark grit and clay	18	0·60	0·70	0·80	1·2	50	19
153			5	Dark grit and clay	18	1·9	2·2	2·5	3·3	75	22
154			10	Dark grit and clay	15	2·1	2·3	2·6	3·2	80	24
160	Teddington,	London	Surface	Fibrous loam	26	1·0	1·1	1·2	1·7	40	14
161	Middlesex	clay	1	Sandy loam	20	0·65	0·70	0·90	1·1	22	14
162	(N.P.L.)		2	Sandy loam	13	0·60	0·65	0·65	1·0	20	12
163			3	Fine gravel	6·5	0·50	0·60	0·65	0·85	20	10
164			5	Coarse gravel	2·9	0·17	0·18	0·21	0·30	12	6·5
166			7	Fine sand	2·6	0·14	0·14	0·15	0·21	7·5	5·0
165			10	Sand and shingle	20	1·2	1·4	1·5	1·8	31	16
167	Wychbold,	Red marls	1	Red clay and loam	15	1·5	1·8	2·0	3·3	49	22
168	Droitwich		2	Red clay	13	3·1	2·9	3·0	4·7	42	23
169	(Midland		3	Red clay	14	2·1	2·2	2·4	4·0	60	29
170	Regional		5	Red clay and stones	15	3·9	4·6	4·8	8·5	55	31
171	Station)		10	Red clay and stones	21	3·7	4·0	4·2	7·0	60	30
172			20	Red clay suspension	31	6·0	7·0	7·5	11·0	65	16
173			30	Red clay suspension	41	6·0	7·0	7·0	12·0	65	38
174			40	Red clay suspension	25	5·5	6·5	6·5	10·0	60	13
175			50	Red clay	27	7·0	7·5	8·5	12·0	60	16
176			100	Grey clay and salt	28	16·0	21·0	22·0	25·0	—*	—
177			150	Red clay and salt	27	—	← about 100 →			—*	—
178			200	Red clay and salt	24	—	← about 100 →			—*	—
179			250	Red clay and salt	22	2·2	2·3	2·4	2·4	30	13
180			300	Red clay and salt	21	7·0	8·0	8·5	17·0	95	24

* The values of the dielectric constant for samples Nos. 176, 177, and 178, were difficult to measure accurately owing to the high conductivity of these samples. Sufficient measurements were made, however, to indicate that the dielectric constant was negligible compared with the conductivity; that is, $\kappa f/(2\sigma) \ll 1$.

conductivity (i.e. above 10^8), the loam and chalk an average value in the neighbourhood of 10^8, and soil of a sandy or gritty nature an appreciably lower conductivity. The conductivity of the surface layer is to some extent influenced by its moisture content, which in turn is very dependent upon the nature of the subsoil. The values obtained on the samples from the deep bore at Droitwich are interesting as showing that the conductivity rises progressively as the depth is increased, attaining a maximum value at 150 and 200 ft. of about 10^{10}, which is comparable with the value for sea water. At the depths of 150 and 200 ft. only the order of the conductivity was obtained, as the condensers used were not suitable for such high values. It was not considered worth while, however, to construct special containers in order to obtain more accurate values for samples from these depths. These high values are most probably due to the slight content of salt which was observed in the samples obtained from these depths. At the greater depths of 250 and 300 ft. the conductivity decreased to about one-tenth of the above maximum value.

The results obtained at Teddington are also of some interest, as showing the presence of a poorly-conducting streak of moderately dry gravel and sand, with moist sand below having from 6 to 10 times the conductivity of the layers immediately above.

(c) Values of Dielectric Constant.

With regard to the results for the dielectric constant recorded in Table 2, it is to be noted that the values of this quantity always decrease as the frequency is raised. In some, but not all, cases the values appear to be increased by the presence of an abnormal amount of moisture. On the whole the values of the dielectric constant are higher for the clays than for the sandy and gritty materials, while the solids give relatively low values, as would be expected from the results of previous investigators. It will be appreciated from all the results obtained that in few cases, and only at the highest frequencies, is the actual value of the dielectric constant of great importance in the study of radio-wave propagation conditions. Where it is of importance the values here obtained are considered to be of sufficient accuracy to be used for calculation.

(d) Conclusions from Electrical Survey.

Within certain limitations this electrical survey may be employed to predict at least the order of the properties of the ground for any site at which the nature of the surface soil and the geological classification are known. The ordinary geological map can, so to speak, be designated in areas of different conductivities. Alternatively, the experience gained in this investigation indicates that a survey of any area of ground can be carried out fairly rapidly, by selecting a few samples of the soil and measuring its constants in the laboratory. For a preliminary survey these measurements could be conducted at audio frequency, with standard equipment for measuring the capacitance and resistance of condensers. A more detailed survey of the selected site could then be carried out at the frequency which is of immediate interest. This procedure has considerable advantages in convenience and rapidity over any field method involving measurements of the tilt of the wave-front or of the attenuation of the field strength with distance. The advantage possessed by these latter methods, however, is that they automatically integrate the contributions to the field at the surface of the currents induced in the soil at different depths. The penetration of the currents in soils of different conductivities is duscussed to some extent in the following section, but the general consideration of this aspect of the problem must remain for future investigation.

(6) Penetration of Electric Waves into the Ground.

From a knowledge of the electrical properties of the ground it is now possible to calculate the rate of attenu-

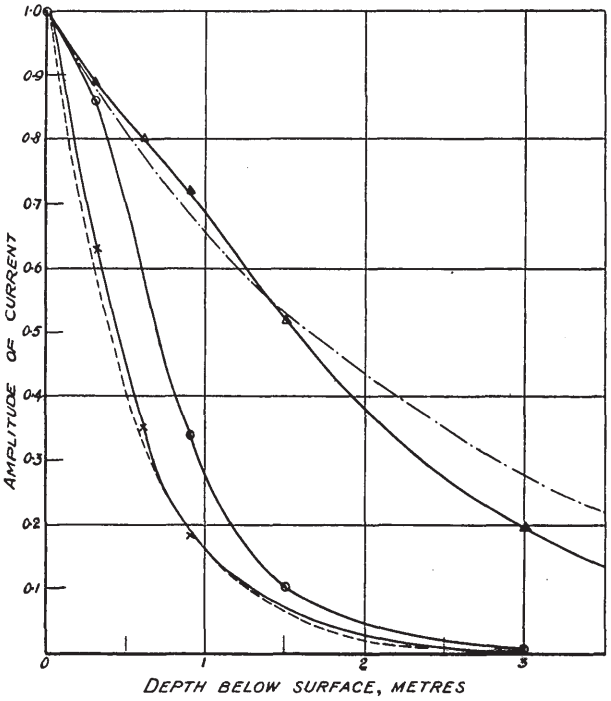

Fig. 6.—Relation between current amplitude and depth below surface for a frequency of 10 000 kilocycles per sec.

ation of the current flowing at any depth as a result of an electrical disturbance produced at the surface. If the amplitude of the current flowing at the surface be I_0 at a frequency corresponding to the wavelength λ, then the amplitude of the current flowing at a depth x is I_x, where

$$I_x/I_0 = e^{-(2\pi x/\lambda)\alpha}$$

and

$$\alpha^2 = \frac{\sigma}{f}\sqrt{\left(\frac{\kappa^2 f^2}{4\sigma^2}+1\right)} - \frac{\kappa}{2}$$

In cases where $\kappa f/(2\sigma) \ll 1$, the formula for α reduces to

$$\alpha = \sqrt{\left(\frac{\sigma}{f} - \frac{\kappa}{2}\right)}$$

With the aid of this formula, graphs showing the relation between current and depth were calculated for a few typical cases from the measured data given in Table 2. In these calculations the average conductivity and dielectric constant were used for each layer of soil for which measurements were available.

The first set of such graphs is presented in Fig. 6, which shows the calculated results for the two sites at Rugby and for Baldock at a frequency of 10 000 kilocycles per sec. From these curves it is seen that at Rugby, over 90 per cent of the current is carried in the first 1·5 metres (5 ft.) of soil, while at Baldock a little less than half the current flows in this depth of

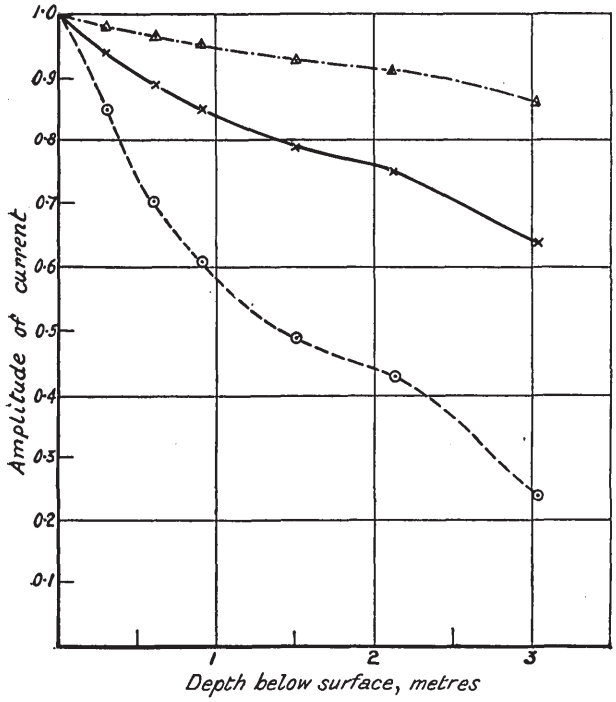

FIG. 7.—Relation between current amplitude and depth below surface, calculated from measurements on soil at N.P.L. (Site No. I).

—·—△—·— Frequency 100 kilocycles per sec.
— x — Frequency 1 000 kilocycles per sec.
—⊙— Frequency 10 000 kilocycles per sec.

soil; an extrapolation of the results shows that a depth of about 4 metres (13 ft.) is required to carry 90 per cent of the current. The same diagram contains curves calculated for two hypothetical soils having uniform conductivity and dielectric constant at different depths. A comparison of these curves with those obtained from the actual measurements shows the accuracy to which, for practical communication purposes, the soils at the two stations may be assumed to have uniform values of 10×10^8 and 50 for Rugby, and 10^8 and 20 for Baldock, for the conductivity and dielectric constant respectively.

The variation of the penetration of the current with frequency is illustrated in Fig. 7, which shows the curves calculated from the measurements on soil from site I at the N.P.L., Teddington, for the three frequencies of 100, 1 000, and 10 000 kilocycles per sec. At the lowest frequency about 86 per cent of the current is flowing at a depth of 3 metres, while at the highest frequency the value is reduced to about 25 per cent. The inflection of the curves at a point corresponding to a depth of about 2 metres is due to the marked decrease in the conductivity of the soil at this site at this depth (5 to 7 ft.). At the lower depth of 3·03 metres the conductivity rises to a value which is actually higher than that at the surface.

With the aid of the results of measurements on samples from Droitwich at greater depths, the graphs in Fig. 8 were calculated. These show the decay in current amplitude with depth down to 18 metres (about

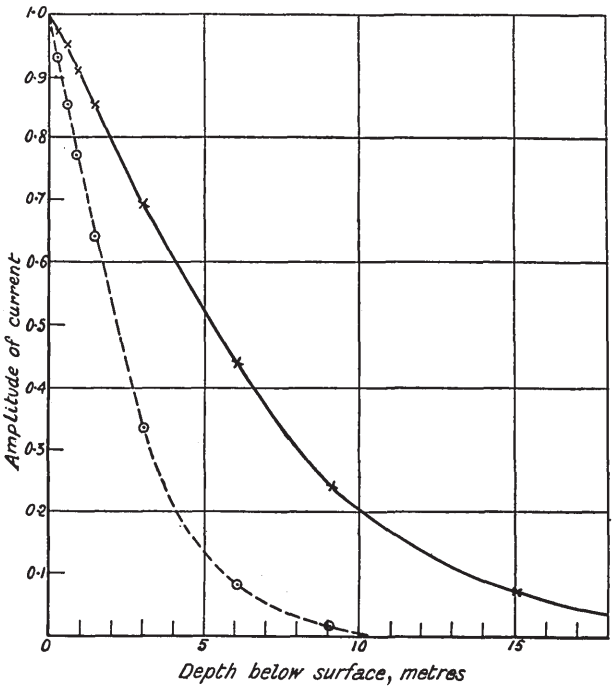

FIG. 8.—Relation between current amplitude and depth below surface, calculated from measurements on soil from Droitwich.

—x— Frequency 100 kilocycles per sec.
---⊙--- Frequency 1 000 kilocycles per sec.

55 ft.) for the two frequencies of 100 and 1 000 kilocycles per sec. Even at the lower frequency the amount of current which flows at depths of more than 30 metres (over 100 ft.) is negligible.

While the graphs shown in Figs. 6, 7, and 8, give some idea of the depth to which currents at various frequencies penetrate in typical soils, it must not be assumed that these indicate the depth of soil which must be taken into account in studying the propagation of electric waves along the surface of the earth. The field at the surface will be determined by the resultant of the field of the arriving waves and of the secondary field due to the currents flowing in the soil. The effective contribution of the latter will naturally decrease rapidly with their depth below the surface, to an extent which must remain for further investigation.

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